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TITLE: PARAMETERS OF A POSSIBLE FRC ADIABATIC COMPRESSION EXPERIMENT

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PARAMETERS OF A POSSIBLE FRC ADIABATIC COMPRESSION EXPERIMENT

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1. Introduction: we describe here a preliminary analysis of an experiment that would address the following research goals for field-reversed configurations (FRC).

(a) test FRC stability with a number of ion gyroradii relative to the plasma radius substantially greater then in present experiments.

(b) increase the electron temperature sufficiently to test the physics of electron energy confinement and of trapped-flux losses.

(c) improve confinement while remaining in a density regime ($n \leq 5\times10^{15}$ cm^{-3}) most likely to be relevant to fusion power production.

Taking the basic constraint of laws of adiabatic compression[1], we consider parameters of a three-stage device: a source, a compression region, and a confinement region. An FRC is formed at low energy in the source (state 1), translated into the compression region (state 2), adiabatically compressed to high energy (state 3), and translated again into the confinement region (state 4). In section 2, we define a final state sufficient to address the above goals, and calculate the required sizes and bank energies of the source and of the compression region. In section 3, we present a particular set of parameters based on a source with present high voltage technology. In section 4, we discuss some of the issues involved in developing FRC formation techniques with lower voltages than in present sources.

2. Calculations: State 4 can be defined by maximizing the parameter $\bar{S} = \int rdr/r_s\rho_i$ which measures FRC magnetization and stability[2]. For typical FRC profiles, $\bar{S}$ can be approximated by $Sx_s/5$, where S is the commonly used ratio R/ρ_{io} and x_s is the ratio of separatrix radius r_s to flux conserver radius r_c. Since S scales as $r_s\sqrt{n_M}$ (n_M is the maximum density), $\bar{S}$ scales as $r_c x_s^2 \sqrt{n_M}$. As indicated in goal (c), we limit ourselves to $n_4 = 5\times10^{15}$ cm^{-3}. We choose a maximum value of 0.8 for x_s to prevent plasma contact with the wall. We also choose $r_c = 17.5$ cm because it is the maximum value compatible with the confinement region of the FRX-C/T experiment[3] (this confinement region could be adequate for the experiment described here). With these choices, one calculates $\bar{S} = 7.1$, a value about 3 times larger than the largest values obtained so far[2,4], so that goal (a) can indeed be met. In addition, by choosing a minimum temperature $T = T_e = T_i = 500$ eV, this state 4 could meet goals (b) and (c), as will be shown in section 3.

The final state just defined is now used to find the required sizes and bank energies of the source and of the compression region. We assume that all states are related to each other by adiabatic reversable processes. For typical FRC pressure profiles, neglecting directional energy (viz. FRC at rest), the adiabatic laws are[1]

$$\ell_s \sim x^{1.9}\beta^{-0.7}r^{0.4}, \; T \sim x^{-2.6}\beta^{0.3}r^{-1.6}, \; n_M \sim x^{-3.9}\beta^{-0.3}r^{-2.4} \qquad (1)$$

where ℓ_s is the length of the separatrix, $x = x_s$, $r = r_c$, and $\beta = 1-x^2/2$. Using Eq. (1) requires that the FRC confinement times in all states be substantially larger than the times (in the range 50 to 100 μs) necessary to translate or compress the FRC.

Figure 1 shows (a) the coil radius r_1, and (b) the bank energy E_1 of the source, that are obtained from Eq. (1) as functions of x_1 and T_1. E_1 is estimated as $\pi\alpha_1(B_0+B_1)^2 r_1^2 \ell_1/2\mu_0$, where α_1 is an efficiency factor taken as 2 (the present FRX-C value). The coil length ℓ_1 and the separatrix length ℓ_{s1} are taken as $8r_1$ and $5r_1$, respectively. The initial bias field B_0 is computed by assuming that 10% of the initial bias flux is retained in state 1, a percentage representative[4] of FRX-C. One observes from Fig. 1 that both r_1 and E_1 are strong decreasing functions of x_1, particularly in the range 0.4 to 0.6. This suggests the strong desirability of formation techniques that can maximize x_1. This observation is also relevant to the compression region, as seen with Fig. 2 where (a) r_2, and (b) E_2 are shown as functions of x_1 and T_1. Fig. 2 is obtained by using Eq. (1), by assuming translations (1→2 and 3→4) at constant plasma pressure, and by taking $x_2 = 0.8$. E_2 is estimated as $\pi\alpha_2(B_3^2-B_1^2)r_2^2\ell_2/2\mu_0$, with $\ell_2 = \ell_{s2}$ and $\alpha_2 = 1.5$. It is important to note that the values of E_2 in Fig. 2b are significantly smaller than the values E_2' that would be required to compress the FRC inside the source, for given initial and final magnetic fields. The ratio $E_2'/E_2 = \alpha_1 r_1^2 \ell_1/\alpha_2 r_2^2 \ell_2$ is typically in the range 3 to 4 for the following reasons:

(i) Translation to a maximum value of x_2 allows an optimum volume utilization. With $\ell_1 = \ell_{s1}$ and $\ell_2 = \ell_{s2}$, translation at constant pressure implies $r_1^2\ell_1/r_2^2\ell_2 \sim r_1/r_2 > 1$. In addition, one always has $\ell_1 > \ell_{s1}$ and one can have an effective value of ℓ_2 that is less than ℓ_{s2} by using several independent banks to compress over a length that decreases in time together with ℓ_s.

(ii) The bank efficiency in the compression region is likely to be better than in the source ($\alpha_1/\alpha_2 > 1$). This is mostly because the source is fed by several banks in parallel. In addition, translation allows a separation between the lower-voltage technology of the compression region and the technology of the source which is likely to be more complicated. This separation is attractive in itself, and may also contribute to a higher value of α_1/α_2.

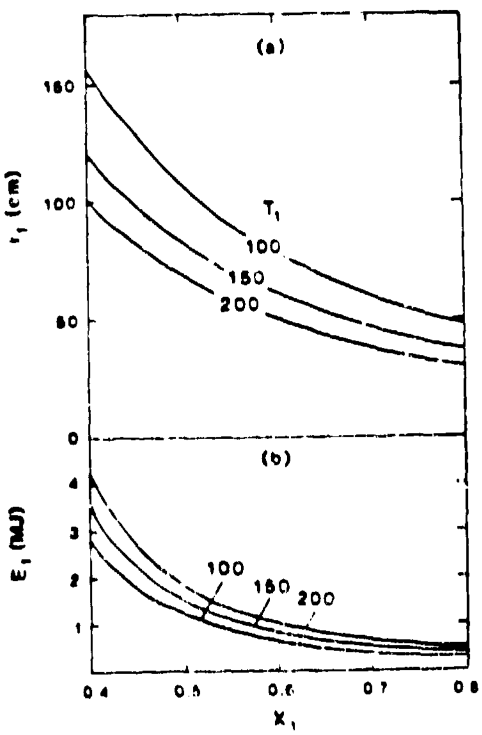

Fig. 1. Size and bank energy of the source as functions of x_1 and T_1.

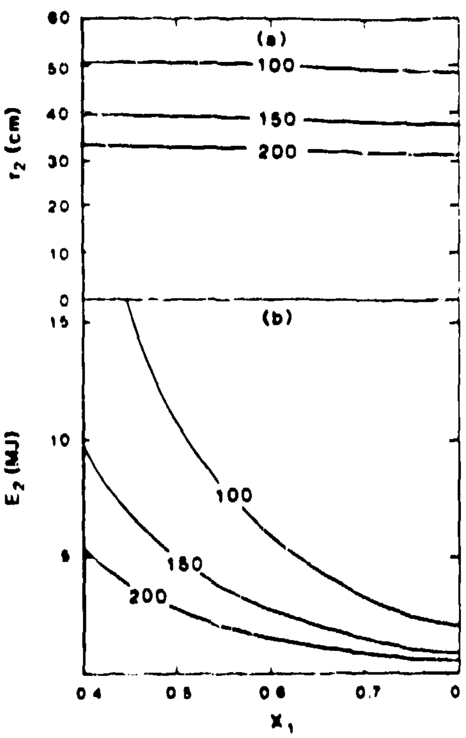

Fig. 2. Size and bank energy of the compression region as functions of x_1 and T_1.

3. An example: Figures 1 and 2 clearly show the sensitivity of the sizes and bank energies to the values of x_1 and T_1. The actual values of x_1 and T_1 depend on the particular formation technique that is used. As will be discussed in section 4, one can estimate with reasonable confidence x_1 and T_1 at the present time only for FRC sources that involve high voltage technology. Therefore, we present in Table 1 a set of parameters for such a source.

Table 1: Plasma parameters based on a source with high voltage technology

State	1	2	3	4
r (cm)	70	38.1	38.1	17.5
x	0.55	0.80	0.50	0.80
n_M (10^{15}cm^{-3})	0.7	0.8	4.6	5.0
T (eV)	154	144	540	500
B (kG)	3.0	3.0	14.1	14.1
ℓ_s (m)	3.2	6.0	2.0	4.4
r_s (cm)	38.5	30.5	18.9	14.0
S	46.3	37.9	57.5	44.3
$\bar{s}$	5.1	6.1	5.7	7.1
τ_N (ms)	2.0	4.0	0.6	1.6
τ_E (ms)	1.0	2.0	0.3	0.8
τ_ϕ (ms)[a]	4.3	2.4	6.7	3.3
$n\tau_E$(10^{12}cm^{-3})[b]	0.6	1.0	1.3	2.6
E_p (kJ)[c]	45	42	157	146

(a) $\tau_\phi=0.15(r_s/10)^2(T/100)^{3/2}$, (b) $n\tau_E=\beta n_M\tau_E$, (c) $E_p=3NT$, $N=(2/3)\pi r_s^2\ell_s n_M\beta$

Steinhauer's formation code[5] is used to define the plasma parameters of state 1 in Table 1. The source is extrapolated from FRX-C, with r_1 = 70 cm, a tube radius of 56 cm, ℓ_1 = 5 m, and is four-fed with 45 KV technology. The values of n_{M1}, T_1, B_1, and x_1 in Table 1 are very similar to those obtained at 5 mTorr fill pressure on FRX-C with a fraction of the main bank[3]. This gives us some confidence that the plasma parameters of state 1 in Table 1 can indeed be achieved (in particular x_1 = 0.55). One calculates B_o ~ 0.8 KG and E_1 ~ 1 MJ. The compression region has r_2 ~ 38 cm, ℓ_2 = 6 m, and E_2 ~ 3 MJ.
The particle confinement times τ_N given in Table 1 are calculated with an analytical formula[6] based on Lower-Hybrid resistivity. These calculated values of τ_N are found to be within 30% of those obtained with earlier numerical work[7]. The energy confinement times τ_E are taken as $\tau_N/2$, to account for energy losses by thermal conduction and radiation in about the same proportion as found[8] in FRX-C. The trapped-flux confinement times τ_ϕ are also extrapolated from FRX-C data, assuming a classical dependence $\tau_\phi \sim r_s^2T_e^{3/2}$. An electron temperature of 540 eV is about 3 times larger than presently achieved[4], and should be sufficient to meet goal (b). The adiabatic compression has the advantage of heating ions and electrons equally, thus facilitating the studies of this goal. If larger temperatures are desired, one can choose to further compress the FRC at the expense of confinement. For example, with E_2 ~ 5 MJ, one can obtain x_3 = 0.39, T_3 = 1 KeV, n_{M3} = 10^{16} cm^{-3}, and B_3 = 30 KG. We note from Table 1 that the values of τ_E and τ_ϕ are sufficiently large to justify the neglect of losses of trapped-flux and of energy. The ratio τ_E/τ_ϕ is smaller than unity for each state, which is required[9] to calculate the values of τ_N and τ_E with a steady-state model. The plasma is much less collisional in all states than in the 20 mTorr FRX-C cases[4]. One observes from Table 1 that the translation into the confinement region provides values of τ_E and $n\tau_E$ that are greater than those

of state 3 by factors of 2.5 and 2, respectively. This justifies the last translation into a region where dc magnetic field also eliminates the need for an efficient crowbar switch in the compression region. The final values of $\tau_E = 0.8$ ms, $n\tau_E = 2.6\times10^{12}$ cm^{-3}s, and $nT\tau_E = 1.3\times10^{12}$ cm^{-3}KeVs are larger than the best present values[4] by about one order of magnitude, thereby fulfilling goal (c).

4. Sources with lower voltage technology: We now consider FRC sources with a more attractive technology than the one in Table 1. A possible source would be a slow theta-pinch[10] for which resistive heating provides most of the required plasma temperature. Assuming for example a voltage of 32 KV around a 70 cm coil radius, the ratio τ_f/τ_A (formation/Alfvèn times) is about 7, which is intermediate between the source of Table 1 ($\tau_f/\tau_A \sim 1$) and ultimate slow sources ($\tau_f/\tau_A >> 1$). Steinhauer's model[5] was used to investigate FRC formation in such an intermediate source, with 32 KV around the coil. Although resistive heating proved adequate for $r_1 = 10$ cm, this heating process was found to rapidly become insufficient as r_1 was increased to 70 cm. This is because resistive heating is tied to the drift parameter v_d/v_i (at the field null) in Steinhauer's model, as is appropriate if dissipation comes from microinstabilities. As r_1 increases, v_d/v_i decreases and resistive heating also decreases. Further theoretical and experimental work is needed to find whether resistive heating may arise independently of the drift parameter, and to find how much heating can be expected from other processes such as axial compression. In particular, the scaling of such a source with respect to size appears a key issue.
Ultimate slow sources (e.g. the rotating magnetic field technique and the coaxial source) have already been considered[11], but the plasma physics involved in the formation process is not yet sufficiently understood. Therefore, there is an insufficient theoretical and experimental data base to allow us at the present time to obtain a self-consistent set of plasma parameters for an example such as the one of Table 1.

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